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Comparisons of satellites liquid water estimates to ECMWF and GMAO analyses, 20th century IPCC AR4 climate simulations, and GCM simulations

Jui-Lin F. Li,[1] D. Waliser,[1] C. Woods,[1] J. Teixeira,[1] J. Bacmeister,[2] J. Chern,[2] B.-W. Shen,[2] A. Tompkins,[3] W.-K. Tao,[2] and M. Köhler[3]

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[1] To assess the fidelity of general circulation models (GCMs) in simulating cloud liquid water, liquid water path (LWP) retrievals from several satellites with passive sensors and the vertically-resolved liquid water content (LWC) from the CloudSat are used. Comparisons are made with ECMWF and MERRA analyses, GCM simulations utilized in the IPCC 4th Assessment, and three GCM simulations. There is considerable disagreement amongst the LWP estimates and amongst the modeled values. The LWP from GCMs are much larger than the observed estimates and the two analyses. The largest values in the CloudSat LWP occur over the boundary-layer stratocumulus regions; this feature is not as evident in the analyses or models. Better agreement is found between the two analyses and CloudSat LWP when cases with surface precipitation are excluded. The upward vertical extent of LWC from the GCMs and analyses is greater than CloudSat estimates. The issues of representing LWC and precipitation consistently between satellite-derived and model values are discussed. **Citation:** Li, J.-L. F., D. Waliser, C. Woods, J. Teixeira, J. Bacmeister, J. Chern, B.-W. Shen, A. Tompkins, W.-K. Tao, and M. Köhler (2008), Comparisons of satellites liquid water estimates to ECMWF and GMAO analyses, 20th century IPCC AR4 climate simulations, and GCM simulations, *Geophys. Res. Lett.*, *35*, L19710, doi:10.1029/2008GL035427.

1. Introduction

[2] Clouds strongly influence global climate through their effects on the Earth's radiation budget [e.g., *Randall and Tjemkes*, 1991]. The importance of low (liquid) clouds cannot be overstated as "cloud feedbacks remain the largest source of uncertainty" in determining Earth's equilibrium climate sensitivity, specifically to a doubling of carbon dioxide [*Intergovernmental Panel on Climate Change (IPCC)*, 2007]. Some evidence for this uncertainty is given in Figures 1a and 1b which illustrates considerable model-to-model disagreement in liquid water path (LWP; g m^{-2}) in the general circulation model (GCM) simulations contributed to the IPCC 4th Assessment Report (20c3m scenario). In the past, global observations of cloud water, particularly vertically-resolved cloud liquid water content (LWC; mg m^{-3}), have not been available for study or model evaluation. Despite significant efforts to derive LWP measurements from passive and nadir-viewing techniques, the large optical thicknesses, multi-layer structure, and mixed-phase nature−including the presence of precipitating hydrometeors (e.g., drizzle), of many clouds has made the estimates from these techniques very uncertain [e.g., *Stephens et al.*, 2008]. The ramifications of this poor constraint for cloud water mass, even in terms of total water path, are evident in the model-to-model disagreement for globally-averaged cloud LWPs shown in Figure 1a. As expected, these differences are exacerbated when considering the spatial patterns of the time-mean values shown in Figure 1b. The significant model-model disagreement for such a fundamental quantity, that has important ramifications in the context of climate change, must be reduced to improve future model climate projections. The recently launched CloudSat mission provides a considerable leap forward in the information gathered regarding tropospheric cloud mass as well as other macro-physical and micro-physical properties [e.g., *Stephens et al.*, 2008]. CloudSat's cloud profiling radar capabilities provide a new view of the global and vertical structure of clouds, in particular the vertical structure of cloud condensate. It is worth noting that, for both the passive and active satellite retrievals and for the models, it tends to be understood that "cloud liquid"(LWC) represents all liquid hydrometeors, and can include suspended cloud liquid and liquid mass in precipitating forms such as rain or drizzle. However, such distinctions are often not clearly made, and certainly not always made consistently amongst satellite retrievals, model parameterizations and/or output from models. In this paper, we examine the level of agreement of LWC/LWP among available satellites estimates, GCMs and analyses. Summarizing remarks include discussion of uncertainties and expected areas of future research.

2. Observations

[3] Satellite observations of liquid clouds are typically either based on passive nadir-viewing or radar sounding techniques. The former offer estimates of vertically integrated LWP, while the latter provide estimates of vertically-resolved LWC. In this study, we mainly focus on LWC/LWP comparisons between models/analyses and satellite retrievals. It is beyond the scope of this paper to describe the details of each of these algorithms and details are left to the referenced literature. Figure 2 illustrates LWP from three products based on passive detection of infrared, microwave and visible radiation, *Clouds And The Earth's Radiant Energy System* (CERES)/Moderate-resolution Imaging Spectroradiometer

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.
[2]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[3]European Centre for Medium-Range Weather Forecasts, Reading, UK.

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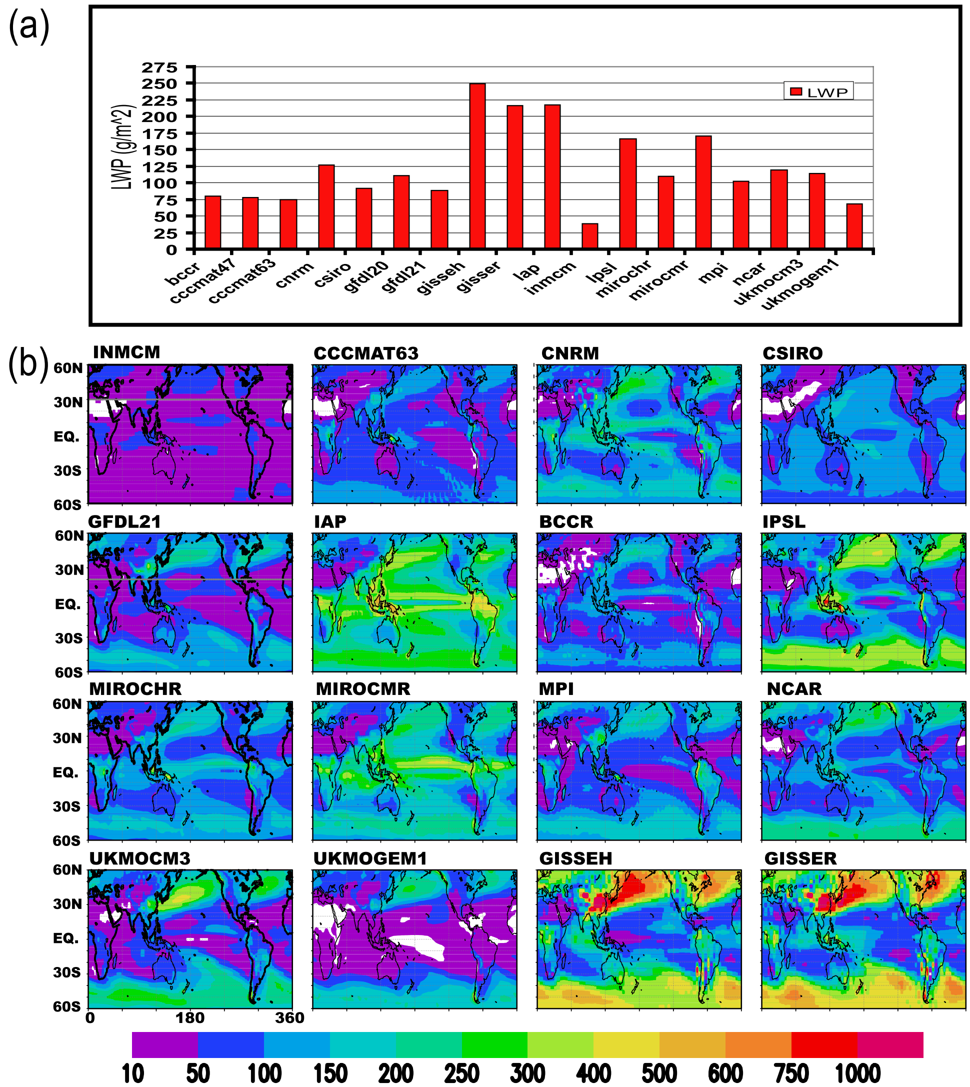

Figure 1. (a) Globally-averaged, multi-year means of cloud LWP from the 1970–1994 periods of the 20th century GCM simulations contributed to the IPCC FAR (20c3m scenario). (b) Multi-year mean values of cloud LWP (g m^{-2}) from 1970–1994 of the 20th century GCM simulations contributed to the IPCC FAR (20c3m scenario). Note the color scale is not linear.

(MODIS) (Figure 2a) [e.g., *Minnis et al.*, 2007], *Special Sensor Microwave/Imager* (SSM/I) (Figure 2b) [*Ferraro et al.*, 2005] and *International Satellite Cloud Climatology Project* (ISCCP) (Figure 2c) [*Rossow and Schiffer*, 1999]. Note that the LWP global average values are in the same order of magnitude between the multi-year mean and individual annual mean (figure not shown). While these products exhibit considerably better agreement in LWP values than the IPCC models shown in Figure 1, there is clear disagreement over the western Pacific Oceans, Intertropical Convergence Zone (ITCZ)/*South Pacific Convergence Zone* (SPCZ) and mid-latitude storm track. Several factors could contribute to this disagreement and include the presence of multi-level, mixed-phase and thick clouds as well as surfaces that have variable emissivity, each of which can represent a significant challenge for passive techniques. Each of these passive estimates is limited to estimating LWP with no/poor profiling capabilities.

[4] CloudSat uses a 94 GHz, nadir-viewing radar to measure backscattered power. The measurements are used to derive cloud and precipitation properties such as LWC (e.g., Figures 2d–2f) and ice water content (IWC) (version 5.1, in CloudSat release 4 [RO4] [*Stephens et al.*, 2008]). The IWC/LWC retrieval is performed with a constraint based on the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses temperature. A condensate profile is derived by using the LWC retrieval for bins warmer than 0°C, the IWC retrieval for bins colder than -20°C, and a linear combination of the two in the intermediate temperature range. CloudSat is expected to be sensitive to both cloud and precipitation sized liquid and ice particles. Therefore retrieved estimates from CloudSat should be expected to represent more than just suspended cloud liquid water/ice water content (e.g., D. E. Waliser et al., Cloud ice: A climate model challenge with signs and expectations of progress, submitted to *Journal of Geophysical Research*, 2008). It is imperative to consider these issues to properly utilize the data for model comparison and validation.

[5] The CloudSat estimates for multi-year mean *total* LWP and the zonal average of the multi-year mean vertically-resolved LWC are shown in Figures 2d and 4a,

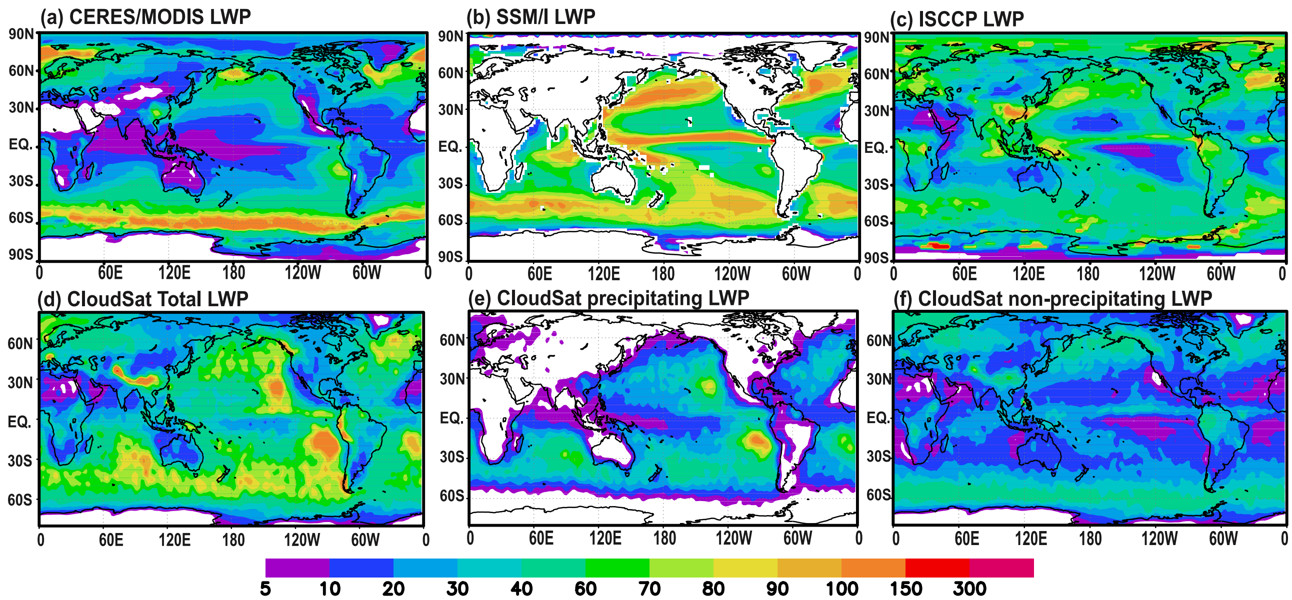

Figure 2. Multi-year mean values of cloud liquid water path (LWP; g m^{-2}) from the all-sky LWP of (a) CERES/MODIS (2001–2005), (b) SSM/I (7/2002–6/2007), (c) ISCCP (Annual mean: 2005), as well as (d) CloudSat (8/2006–7/2007) for total LWP, (e) CloudSat LWP associated with precipitation at the surface, and (f) CloudSat non-precipitating LWP.

respectively. While these figures represent a preliminary estimate of *total* LWP/LWC from CloudSat, it would be valuable to have a form of GCM validation for the "cloud" liquid fields, that isn't contaminated with larger liquid precipitating hydrometeors. As done by Waliser et al. (submitted manuscript, 2008), we consider conditionally sampling of the CloudSat LWP/LWC values to remove cases flagged as precipitating at the surface. This is intended to filter out columns that have larger falling hydrometeors in them and thus serve as a preliminary estimate of the LWP/LWC (Figures 2f and 4c) for "clouds" only profiles for model-data comparisons. Our preliminary method to exclude retrievals when precipitating hydrometeors are present is to use the CloudSat precipitation flag that identifies retrievals associated with precipitation at the surface. This can be either solid or liquid precipitation, with the latter including "drizzle" from boundary layer clouds (see Text S1 of the auxiliary material).[1] Figure 2e (Figure 4b) shows the CloudSat annual mean LWP (zonal mean LWC) for retrievals flagged as "precipitating" at the surface. Note that for the Tropical regions, most of this LWP (~90% in most areas) is also flagged as drizzle (not shown). The CloudSat LWP (LWC) for all cases not flagged as precipitating at the surface is shown in Figure 2f (Figure 4c). Figure S1 shows the percentage of total samples removed in the cases that are flagged as having precipitation at the surface (S1a) and total number of CloudSat samples (S1b). In regions of appreciable LWC (see Figure 4a), the samples removed account for about 5–30% of the total samples. In addition, a comparison of the different satellite LWP estimates in Figure 2 shows that over the boundary-layer stratocumulus regions (e.g., off coasts of California, Peru, Northwest Africa etc) the total CloudSat LWP values (Figure 2d) are considerably larger than those estimates based on passive techniques. However, in the ITCZ, SPCZ and oceanic storm track regions, the SSM/I LWP values are generally well over a factor of two larger than those from CloudSat, CERES/MODIS and ISCCP.

[6] There is also considerable disagreement among the four products over the western Pacific and Indian Ocean warm pool regions, with the CERES/MODIS (SSM/I) being the lowest (highest) around 10 (100) g m^{-2}. In terms of overall magnitude, CloudSat and ISCCP appear to agree best, although there are differences in morphology particularly in the stratocumulus regions mentioned above. The exact basis for the disagreements in these satellite estimates is beyond the scope of this paper but is likely to be associated with different sampling strategies, particle size sensitivities of the sensors, and retrieval algorithms, and how these account for the multi-layer and mixed-phase structures of clouds, when applying these estimates to model diagnosis and validation [e.g., *Horváth and Davies*, 2007]. Of particular relevance is that most of the estimates consider/include all liquid water in the column–to the extent their sensor/algorithms are sensitive to it.

3. Results

[7] Analyses data from ECMWF and NASA Goddard *Global Modeling and Assimilation Office (*GMAO) Modern Era Retrospective-Analysis for Research and Application (MERRA) as well as GCMs from NCAR Community Atmosphere Model V.3 (CAM3), Goddard Earth Observing System V.5(GEOS5) and the multi-scale finite volume multi-scale-modeling framework (fvMMF) [*Tao et al.*, 2008] are used in this study. All the model data have been converted from cloud water mixing ratio (kg kg^{-1}) to LWC (mg m^{-3}) using model temperatures and pressures and re-gridded to a common 2° × 2° latitude-longitude grid.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL035427.

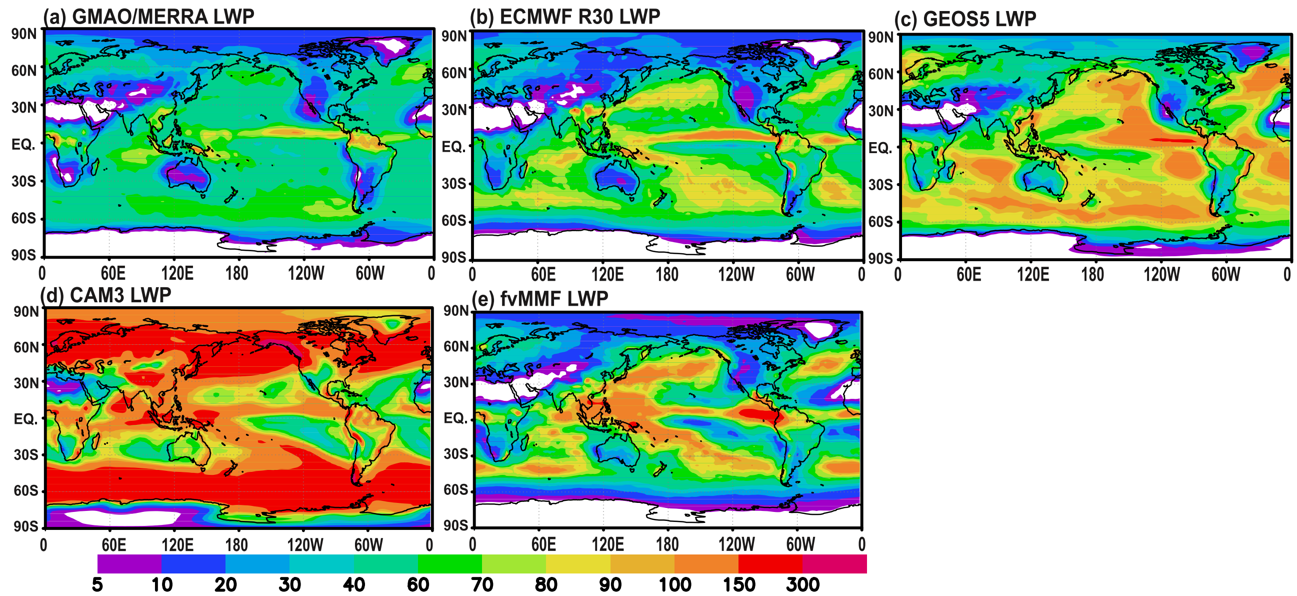

Figure 3. Multi-year mean values of cloud liquid water path (LWP; g m^{-2}) from (a) NASA GMAO/MERRA (01/1979–10/1979), (b) ECMWF R30 analysis (08/2005–07/2006), (c) GEOS5 AGCM (01/1999–12/2002), (d) NCAR CAM3 (1979–1999), and (e) fvMMF (01/2005–12/2006).

3.1. ECMWF and GMAO MERRA Analyses

[8] The analyses from the ECMWF and the GMAO MERRA are examined. For this comparison, the LWC values from the R30 version of the IFS system for the period 8/2005 to 7/2006 are used while the MERRA values are from the available 10-month period 1/1979–10/1979. In general, the geographical distribution of LWP is in fairly good agreement between the two analyses, except for the storm track regions where ECMWF (MERRA) is relatively high (low). Compared to the observed estimates, the ECMWF and the SSM/I values are in general agreement, quite likely due to the assimilation of the latter by the IFS. The values from the analyses tend to agree best in terms of morphology with the CloudSat LWP that only includes non-precipitating conditions although the analyses values are at least a factor of 2–3 higher in magnitude. Neither analyses exhibits the large peak values evident in the *total* CloudSat LWP over the boundary-layer stratocumulus cloud regions. It should be noted that the latter could be an artifact of the retrievals as validation exercises are still ongoing.

[9] Figure 4 shows the zonal and multi-year mean vertical profiles of LWC from CloudSat *total* LWC (Figure 4a) and LWC associated with the retrievals flagged as having precipitation at the surface (Figure 4b) and no precipitation at the surface (Figure 4c). It is evident that the LWC associated with conditions where precipitation is detected at the surface dominates the LWC contribution in the tropical and subtropical regions. For nearly all regions, as well as for the total LWC and the conditionally sampled values, CloudSat indicates that the greatest concentration of LWC is at levels below 750 hPa. Smaller values of LWC (2 mg m^{-3}) extend up to about 600 hPa near the 0°C line. While this is generally true for the MERRA and ECMWF analyses as well (Figures 4d and 4e), the general morphology of the IWC in the latitude-pressure plane varies considerably between the observed and analyses values. Both analyses have more LWC extending above 750 hPa than exhibited by CloudSat but not in a manner that agrees between the two. It is worth re-iterating at this time that CloudSat LWC values are artificially constrained to only occur in regions warmer than 0°C and are mixed with ice in the temperature range −20 to 0°C (see Section 2).CloudSat retrievals do not allow LWC at temperatures below −20°C, thus limiting the depth over which it may extend in the atmosphere. For this reason, model values of LWC may extend to a greater height than estimates from CloudSat.

3.2. GCM Simulations

[10] Figure 3 shows the multi-year mean values of LWP from GEOS5 (Figure 3c), NCAR/CAM3 (Figure 3d) and fvMMF (Figure 3e). The multi-year mean values of LWP for each model indicate overall magnitudes that are generally much larger than the observed estimates shown in Figure 2. This is especially the case in the extra-tropics for NCAR/CAM3, and to some extent GEOS5. When considering the observed, analyses and GCM values, the best agreement is shown among the SSM/I, ECMWF and fvMMF. Considering the models as a whole, the disparity in magnitude and spatial structure are substantial. NCAR/CAM3 and fvMMF exhibit an ITCZ structure in their tropical pattern of LWP, as does CloudSat, SSM/I, ISCCP, GMAO and ECMWF. On the other hand, GEOS5 and CERES/MODIS exhibit something quite different with relatively low values over the warm pool regions. The very wide disparity in modeled values is reminiscent of the poor agreement exhibited by the GCMs in Figure 1. Figure S2 illustrates the global, extra-tropical and tropical mean IWP values for the GCMs, the satellite retrievals including CloudSat, MERRA and ECMWF. This plot demonstrates that, most models/analyses have extra-tropical LWP values that are smaller than the tropical values except for CAM3, the extra-tropical LWP values are larger than tropical averages by a factors of two. The ISCCP and CloudSat retrievals show the extra-tropical

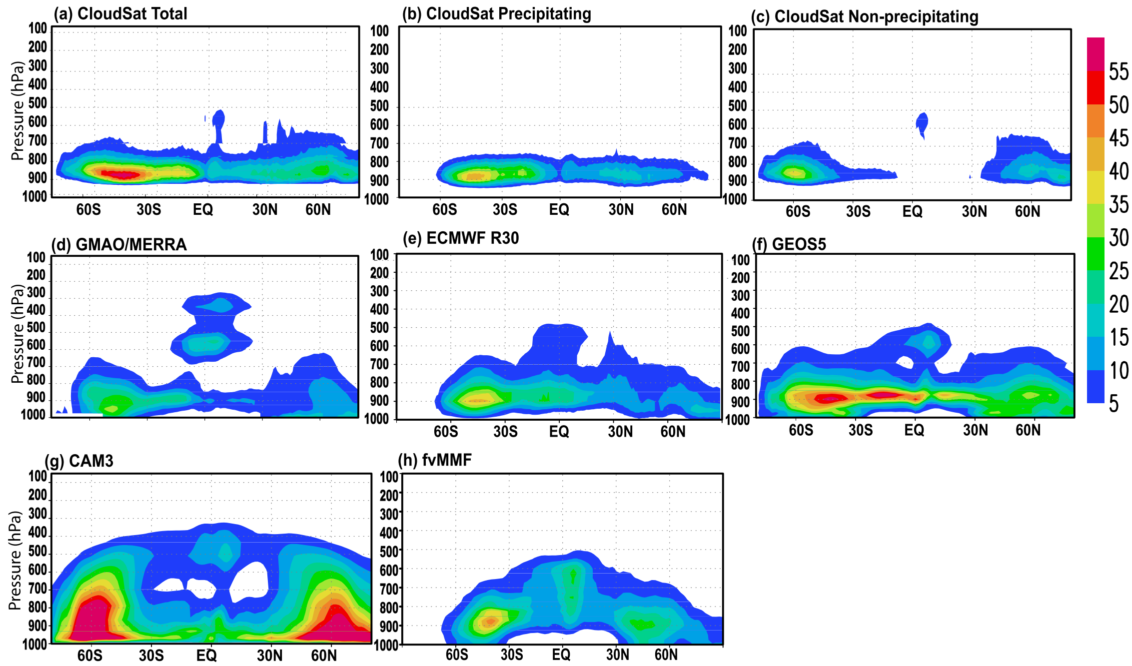

Figure 4. Multi-year mean zonal average values of cloud liquid water content (LWC; mg m^{-3}) from (a) CloudSat (8/2006–7/2007) for total LWC, (b) LWC associated with precipitation at the surface, (c) non-precipitating LWC, (d) NASA GMAO/MERRA (01/1979–10/1979), (e) ECMWF R30 analysis (08/2005–07/2006), (f) GEOS5 AGCM (01/1999–12/2002), (g) NCAR CAM3 (1979–1999), and (h) fvMMF (01/2005–12/2006).

and tropical values to be similar, except for the CERES/MODIS values which exhibit larger extra-tropical values.

[11] Figure 4 shows the zonal and multi-year mean values of LWC from GEOS5 (Figure 4f), NCAR/CAM3 (Figure 4g) and fvMMF (Figure 4h). The CloudSat zonal mean values are shallower than any of the model distributions, and may be related to the temperature conditions used in the IWC/LWC partitioning in the CloudSat retrieval described in the previous section. For each of the GCM representations, non-zero LWC values extend well above 700 hPa, particularly in the Tropics. However, an extreme outlier in this regard is the zonal mean profile from NCAR/CAM3 that exhibits very high LWC values extending up to and above 700 hPa in the extra-tropics. Overall there are considerable differences in the vertical distributions of LWCs exhibited by the GCMs, analyses and retrieved estimates. These are likely related to the fact that different temperature constraints are used on the IWC/LWC partition for the models and the CloudSat retrievals (See Text S1). These dramatic differences imply considerable and important differences in the diabatic heating associated with the clouds–both the radiative and latent heating, and their effects on the large-scale circulation.

4. Summary and Discussion

[12] We have examined the level of agreement of LWP and/or LWC among four satellites estimates, the GCM simulations contributed to the IPCC 4th Assessment Report, three GCMs simulations with prescribed SSTs and two analyses. The interannual variability of model/data LWP is much smaller (figure not shown) than the large spread of LWP values suggested by the model-model, data-data and model-data results given. Significant spatial disagreement for LWP is found in model-to-model comparisons among the GCMs utilized in the most recent IPCC assessment (Figure 1). This disagreement includes both widely varying magnitudes (almost a factor of 100) and considerable differences in spatial patterns. This model-model disagreement extends to an additional set of GCMs with various levels of sophistication (Figures 3 and 4).

[13] Four satellites estimates of cloud liquid water are compared. The geographical distribution of the derived LWP measurements exhibit considerably disagreement in most areas. Over the boundary-layer stratocumulus regions, the total CloudSat LWP values are significantly larger than all the other estimates based on passive techniques.

[14] To help make more meaningful model-data comparisons, we apply conditional sampling for CloudSat LWP/LWC values to exclude retrieved profiles flagged as precipitating at the surface (Figures 2f and 4c). In this way, a better agreement in terms of morphology was found between "non-precipitating" CloudSat LWP and from the analyses. The analyses values, however, are larger by a factor of 2–3 in comparison to total CloudSat LWP and do not exhibit the large peak LWP values evident in the *total* CloudSat LWP over the boundary-layer stratocumulus cloud regions. Both GEOS5 and CERES/MODIS exhibit relatively low bias over the warm pool regions. The best model-analysis-data agreement tends to be found between the SSM/I, ECMWF and fvMMF LWP.

[15] There are considerable differences in the zonally-averaged latitude-pressure plane of LWC distributions exhibited by the GCMs, analyses and CloudSat retrievals. The differences might be due to the different temperature constraints applied when partitioning IWC and LWC within the models and the CloudSat retrievals (see Section 3), and quite possibly other retrieval or model shortcomings. In

addition, these differences in the vertical structure of liquid water mass imply differences in the diabatic heating associated with the clouds and its impact on the large-scale dynamics.

[16] Our near-term focus is on identifying the potential causes for the differences found in this study, particularly how the retrievals and models account for suspended versus falling liquid water. We are currently extending our investigation to consistently sample the GCM LWC values by removing LWC values when there is coincident surface rain. Furthermore, we will compare the *total* LWC CloudSat retrievals to GCM LWC and LWP that allow for precipitating forms of liquid to exist at all grid levels between time steps (e.g., NASA fvMMF).

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J. Bacmeister, J. Chern, B.-W. Shen, and W.-K. Tao, NASA Goddard Space Flight Center, Code 913, Building 22, Room 118, Greenbelt, MD 20771, USA.

M. Köhler and A. Tompkins, European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading RG2 9AX, UK.

J.-L. F. Li, J. Teixeira, D. Waliser, and C. Woods, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 183-601, 4800 Oak Grove Drive, Pasadena, CA 91109, USA. (jli@jpl.nasa.gov)